Renewable and Sustainable Energy Reviews 25 (2013) 462–469

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Effect of reference state on the exergoeconomic evaluation of geothermal district heating systems

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A R T I C L E I N F O

Article history:
Received 26 January 2013
Received in revised form
27 April 2013
Accepted 7 May 2013
Available online 5 June 2013

Keywords:
Geothermal energy
District heating
Exergoeconomic analysis
MOPSA method
Ambient temperature

A B S T R A C T

The exergy cost structure of the geothermal district heating system (GDHS) is investigated by using an exergoeconomic method called as the modified productive structure analysis (MOPSA). A parametric study is also conducted to show how exergy cost flow rates change with the reference state (ambient temperature). As a comprehensive case study, the Afyon GDHS in Afyonkarahisar, Turkey is considered. The actual thermal data taken from the technical staffs as 2.3 °C for January (case 1) and 10.2 °C for February (case 2), 2010 in 100% load condition are collected for this study. Mechanical and thermal exergy flow rates, entropy production rates and exergy cost flow rates for each component in the Afyon GDHS are calculated using these two actual data sets. The results show that the exergy efficiencies of the overall system for these two cases are found to be 25.34% and 22.78%, respectively. And, the largest exergy cost loss occurs in the heat exchangers with 52.49% and 64.91% for cases 1 and 2, respectively. The unit exergy costs are found as $c_P > c_T > c_S > c_Q$ for the actual data sets in each case. In addition, ambient temperature has a big impact on the exergies and costs of GDHSs.

Contents

1. Introduction

Nowadays, there are essentially two key solutions to the current energy and environmental problems namely renewable energies and efficient energy use. First, renewable energies may cover a broad spectrum from solar to geothermal energy. In this particular paper the energy source is geothermal energy. Geothermal energy can be used for a large variety of applications, such as electricity generation, heating, cooling, industrial drying, fermentation, balneological utilization, distillation and desalination depending on the temperature of the source [1]. In the literature, there are various research studies (e.g., [2–8]) on various aspects of geothermal energy and its utilization. One of them is the district heating. Improvement in performance of a geothermal district heating system (GDHS) is a very effective mean to decrease energy consumption. The importance of energy efficiency is also linked to economic problems.

Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components. Furthermore, exergoeconomic analysis estimates the unit cost of products such as electricity and steam and quantifies monetary loss due to irreversibility. Also, this analysis provides a tool for the optimum design and operation of complex thermal systems. At present, such analysis is in great demand because proper estimation of the production costs is essential for companies to operate profitably [9]. The exergoeconomic analysis

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.05.018

Nomenclature

a	annual operating hour (h/year)
C	unit cost (US$/kWh)
$\dot{C}$	monetary flow rate (US$/year or US$/h)
Ex	exergy (kJ)
$\dot{E}x$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
i	interest rate (%)
$\dot{m}$	mass flow rate (kg/s)
n	lifetime (year)
P	pressure (kPa)
$\dot{Q}$	rate of heat (kW)
s	specific entropy (kJ/kg K)
S	salvage value
$\dot{S}$	entropy rate (kW/K)
T	temperature (°C or K)
$\dot{W}$	work rate, power (kW)
$\dot{Z}$	capital cost rate

Greek symbols

ε	exergy or second law efficiency (%)
η	energy or first law efficiency (%)
ϕ	maintenance factor
ψ	flow exergy (kJ/kg)

Subscripts

cv	control volume
d	natural direct discharge
$dest$	destroyed
he	heat exchanger
i, j	successive number of elements
in	inlet
k	location
mp	mixing pool
out	outlet
P	mechanical
Q	heat
r	re-injected geothermal fluid
T	thermal
Tot	total
tw	thermal water
usf	useful
w	well-head
W	work or electricity
0	reference state

Superscripts

P	mechanical
Q	heat
T	thermal
W	work or electricity

Abbreviations

CRF	capital recovery factor
ECC	energy consumption cycle
EDC	energy distribution cycle
EPC	energy production cycle
GDHS	geothermal district heating system
MOPSA	the modified productive structure analysis
PW	present worth
PWF	present worth factor

is a method that combines exergy analysis with economic analysis. The method provides a technique to evaluate the cost of inefficiencies or the costs of individual process streams, including intermediate and final products [10], as determined for a combined heat and power system [11]. Exergoeconomics is currently a powerful tool to study and optimize an energy system. The application field is the evaluation of utility cost as products or supplies of production plants, the energy cost between process and operations of an energy converter. These costs are applicable in feasibility studies, in investment decisions, on comparing alternative techniques and operating conditions, in a cost-effective section of equipment during an installation, an exchange or expansion of an energy system [12].

As far as some studies conducted on exergoeconomic analyses and assessments are concerned, Kim et al. [13] provided a theoretical basis for the exergy-costing method suggested by Lozano and Valero [14] to a cogeneration system based on a 1000-kW gas turbine with a waste-heat boiler as thermal system. Kwon et al. [15] studied a thermodynamic for the effect of the annualized cost of a component on the production cost in 1000 kW gas-turbine cogeneration system by utilizing the generalized exergy balance and cost-balance equations developed previously. Kwak et al. [9] performed exergetic and thermoeconomic analyses for a 500-MW combined cycle plant using modified productive structure analysis (MOPSA). Kwak et al. [16] performed exergetic and thermoeconomic analysis for a 200-kW phosphoric acid fuel cell plant which offers many advantages for co-generation in the aspect of high electrical efficiency and low emission. This fuel cell system may be viable economically when the initial investment cost per power is reduced to the level of the gas turbine co-generation plant of 1500US$/kW. Kwak et al. [17] investigated the cost structure of the CGAM system by using a thermoeconomic method called MOPSA. Oktay and Dincer [18] presented an application of an exergoeconomic model, which included both exergy and cost accounting analyses for a GDHS in Balikesir/Turkey. They applied cost balance equation to each component of the system and to each junction while they solved a set of equations to calculate unit costs of various exergies. They obtained the lost cost of each component of the system. Some configurations for the GDHS were also considered and compared in the analysis, which used appropriate exergy and cost balance equations. Hepbasli [19] reviewed the GDHSs in terms of three aspects, namely energetic, exergetic and exergoeconomic analyses and assessments. Coskun et al. [20] proposed a modified exergoeconomic model for geothermal power plants using exergy and cost accounting analyses. They presented a case study for the Tuzla geothermal power plant system in Turkey to illustrate an application of the modified exergoeconomic model.

The present paper is the study on an exergoeconomic analysis called as the modified productive structure analysis (MOPSA) for a GDHS. The aim of this study is to find unit exergy costs of a GDHS and to show how exergy cost flow rates change with the ambient temperature. The Afyon GDHS located in the city of Afyonkarahisar/Turkey is therefore selected for exergy-cost evaluation. The system operation is described based on Refs. [21–24]. In the Afyon GDHS, the required mass flow rates according to the changing conditions (especially ambient temperature) in the system are controlled manually. The mass flow rates are not automatically controlled and therefore the data are insufficient. It was observed that there is an

uncertainty about the process of controlling the mass flow rate. Due to this reason, to make an accurate analysis, the required data are collected on two different dates (January 20 and February 23, 2010) for comparison purposes. Using these different data sets, it is aimed to show how exergy cost flow rates change with the ambient temperature. Exergoeconomic analysis procedure and formulations are developed for the present Afyon GDHS using methods in Refs. [13–20]. The MOPSA of thermal systems are utilized for this purpose. This procedure is used for obtaining exergy cost values for the system components. The results obtained are discussed in this study.

2. A case study: the Afyon GDHS

The Afyon geothermal district heating system (GDHS) was founded in 1994 to provide residential heating for buildings by using geothermal water and to provide hot water for commercial greenhouses by using re-circulated geothermal fluid. The Afyon GDHS was initially designed for 10,000 residences equally but today, 4613 of these residences are heated. The heat source of the Afyon GDHS originates from the Omer-Gecek geothermal field, 15 km northwest of Afyonkarahisar City. An average reservoir temperature of wells in this field is 105 °C. Potential of the Afyon GDHS is 48.333 MW_t. The Afyon GDHS consists mainly of three cycles: (a) energy production cycle (EPC), (b) energy distribution cycle (EDC), and (c) energy consumption cycle (ECC). A schematic of the Afyon GDHS is shown in Fig. 1.

Here, the geothermal fluid collected from the four production wells is stored in the mixing pool with a total mass flow rate of about 175 kg/s. The geothermal fluid is then pumped through the main pipeline to the geo-heat mechanical room of the Afyon GDHS in Afyonkarahisar. And the geothermal fluid is sent to the six heat plate exchangers at a 16 million kcal/h total capacity in the geo-heat mechanical room and is cooled to about 45–50 °C. The geothermal fluid is then discharged via natural direct discharge and re-injected. Also, the clean hot water is pumped to the six exchangers and then outgoing water is sent to the heat exchangers which are constructed under all buildings on the zones. The mean temperatures of clean hot water obtained during the operation of the Afyon GDHS are about 60/45 °C for this cycle.

3. Analysis

The balance equations for mass, exergy and cost can be written for the Afyon GDHS and its components under steady-state steady-flow control volume conditions. Also, these equations were used by some earlier researchers (e.g., [21–27]). For the Afyon GDHS, the mass balance equation is written as follows:

$$\sum_{i=1}^{n} \dot{m}_{w,i,Tot} - \dot{m}_{mp} - \dot{m}_r - \dot{m}_d = 0 \quad (1)$$

where $\dot{m}_{w,i,Tot}$ is the total mass flow rate at wellhead, $\dot{m}_r$ is the flow rate of the reinjected geothermal fluid, $\dot{m}_{mp}$ is the flow rate of the

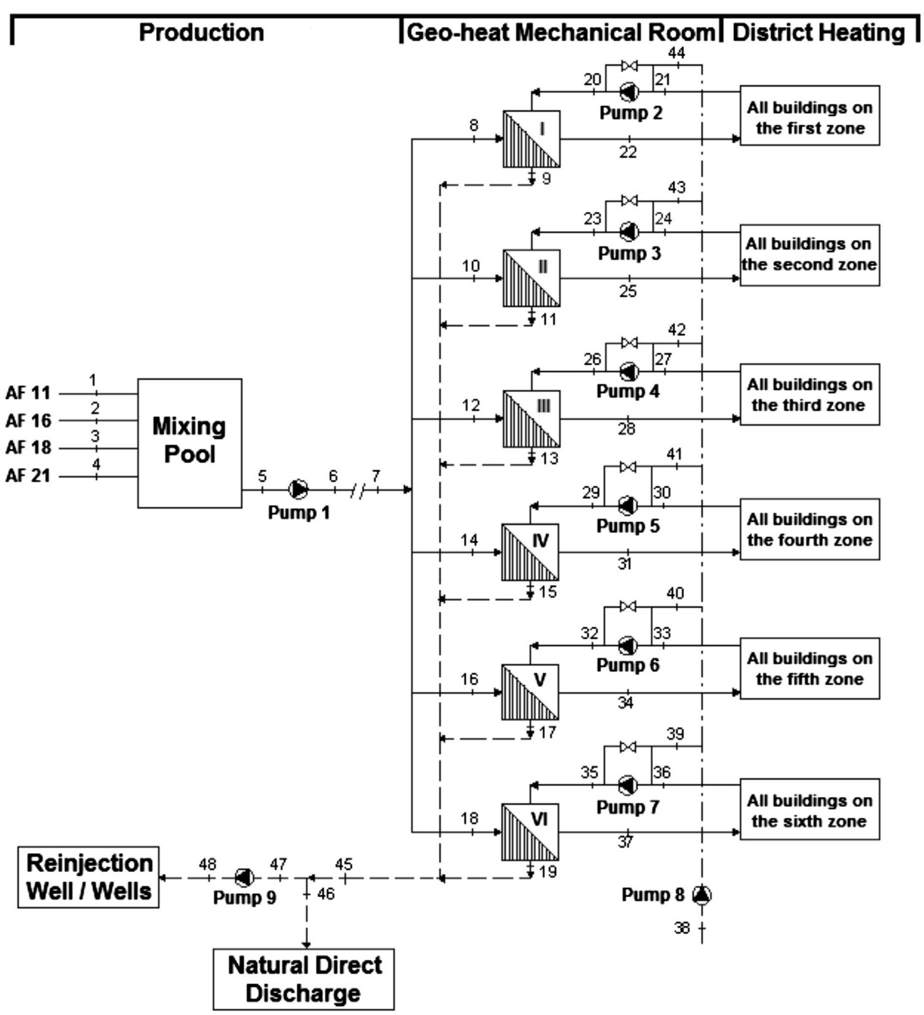

Fig. 1. Schematic diagram of the Afyon GDHS (I–VI: heat exchangers).

remained geothermal fluid in mixing pool, and $\dot{m}_d$ is the mass flow rate of the natural direct discharge.

The general exergy rate balance can be expressed as

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} = \dot{E}x_{dest} \quad (2)$$

and

$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum\dot{m}_{in}\psi_{in} - \sum\dot{m}_{out}\psi_{out} = \dot{E}x_{dest} \quad (3)$$

The geothermal fluid exergy inputs from the production field of the Afyon GDHS are calculated from

$$\dot{E}x_{in} = \dot{E}x_{brine} = \dot{m}_{w,Tot}[(h_{brine}-h_0)-T_0(s_{brine}-s_0)] \quad (4)$$

The exergy destructions in the pump, heat exchanger, mixing pool and system itself of the Afyon GDHS are calculated as follows:

$$\dot{E}x_{dest,pump} = \dot{W}_{pump} - (\dot{E}x_{out} - \dot{E}x_{in}) \quad (5)$$

$$\dot{E}x_{dest,\ he} = \dot{E}x_{in} - \dot{E}x_{out} \quad (6)$$

$$\dot{E}x_{dest,\ mp} = \dot{E}x_{in} - \dot{E}x_{out} \quad (7)$$

$$\dot{E}x_{dest,\ system} = \sum\dot{E}x_{dest,\ pump} + \sum\dot{E}x_{dest,\ he} + \sum\dot{E}x_{dest,\ pipes} \quad (8)$$

The energy and exergy efficiencies of the Afyon GDHS can be defined respectively as

$$\eta_{system} = \frac{\dot{E}_{useful,\ he}}{\dot{E}_{brine}} \quad (9)$$

$$\varepsilon_{system} = \frac{\dot{E}x_{useful,he}}{\dot{E}x_{brine}} = 1 - \frac{\dot{E}x_{dest} + \dot{E}x_r + \dot{E}x_d + \dot{E}x_{mp}}{Ex_{brine}} \quad (10)$$

The exergy efficiency of a heat exchanger is basically defined as

$$\varepsilon_{he} = \frac{\dot{m}_{cold}(\psi_{cold,out} - \psi_{cold,in})}{\dot{m}_{hot}(\psi_{hot,out} - \psi_{hot,in})} \quad (11)$$

The exergy-cost-balance equations, developed by Oh et al. [28] and Kim et al. [13], were applied to the Afyon GDHS for performance assessment purposes. Using this methodology, the cost-balance equation was written for each component of the whole system and to each junction. Thus a set of equations for the unit costs of various exergies was obtained for solution. Solving such equations provided the monetary evaluations of various exergy (thermal, mechanical, etc.) costs, as well as the unit cost of useful heat of the thermal system. The exergy-balance equation for the non-adiabatic components is modified to reflect the exergy losses due to heat transfer. The general exergy-balance equation applicable to cost equation is written as [29]

$$\dot{E}x^Q_{tw} + \dot{E}x^W + \left(\sum_{input}\dot{E}x_i^T - \sum_{outlet}\dot{E}x_j^T\right) + \left(\sum_{input}\dot{E}x_i^P - \sum_{outlet}\dot{E}x_j^P\right)$$
$$+T_0\left(\sum_{input}\dot{S}_i - \sum_{output}\dot{S}_j + \frac{Q_{CV}}{T_0}\right) = \dot{E}x^Q_{usf} \quad (12)$$

where $\dot{Q}_{CV}$ denotes the heat transfer interaction between a component and environment. Considering a unit exergy cost to every separated exergy stream, the exergetic cost-balance equation can be written, according to the exergy-balance equation as given above, as

$$\dot{E}x^Q_{tw} + \dot{E}x^W c_W + \left(\sum_{input}\dot{E}x_i^T - \sum_{outlet}\dot{E}x_j^T\right)c_T + \left(\sum_{input}\dot{E}x_i^P - \sum_{outlet}\dot{E}x_j^P\right)c_P$$
$$+T_0\left(\sum_{input}\dot{S}_i - \sum_{output}\dot{S}_j + \frac{Q_{CV}}{T_0}\right)c_S + \dot{Z}_{(k)} = \dot{E}x^Q_{usf}c_Q \quad (13)$$

where $\dot{Z}_{(k)}$ stands for all financial charges associated with owning and operating the kth plant component. The stream exergy is also separated into thermal and mechanical exergies. Here, the exergy costing method based on the above given equations MOPSA (modified productive structure analysis), developed by Lozano and Valero [14], was employed. In order to calculate annualized cost of the equipment $\dot{Z}_{(k)}$ inside the control volume, the annualized (or levelized) cost method is employed, as presented in Bejan et al. [30], to calculate the capital costs of system components

$$\dot{Z}_{(k)} = \frac{\phi_k\dot{C}_k}{3600a} \quad (14)$$

with

$$\dot{C}_k = PW_k CRF(i,n) \quad (15)$$

and

$$PW_k = c_k - S_{k,n}\ PWF(i,n) \quad (16)$$

where ϕ is the maintenance factor, $\dot{C}$ is the annualized cost ($/year), a is annual operating hours (h/year), PW is the amortization cost (present worth) for any particular plant component, CRF (i,n) is the capital recovery factor, S is the salvage value and PWF is the present worth factor. In this regard, the salvage cost and annual operating time are assumed as 10% of the capital cost and 5040 h/year (24 h × 210 days for a year), respectively. The maintenance cost is taken into consideration through the factor ϕ_k=1.06 for each of the system components whose average expected life (n) is assumed to be 15 years. The interest (i) rate and the unit electricity price are taken as 12% and 0.2233US$/kWh according to Turkey's 2010 year status, respectively. It must be kept in mind that the given economic parameters are used for each case (cases 1 and 2). For more detailed information on exergy-cost topics (MOPSA), Refs. [13–20] can be referred.

4. Results and discussion

In this study, the Afyon geothermal district heating system (GDHS) is described and its balance equations are written for mass, exergy and cost in the system and its components. An application of a modified productive structure analysis (MOPSA), through exergy and cost accounting analyses, to the Afyon GDHS for the entire system and its components is presented. In the analysis, the actual system data sets (temperature, pressure, and flow rate) that were recorded in January 20 (case 1) and February 23 (case 2) 2010 for 100% load condition of the Afyon GDHS were taken from the technical staffs/operators in accordance with their state numbers as specified in Fig. 1.

Here, an example calculation procedure is shown based on actual data for case 1 (as of January 20, 2010). Thus, all these actual data, and mechanical and thermal exergy flow rates and entropy production rates, which are calculated using the Engineering Equation Solver (EES) software, at various state points of the system are given in Table 1 for case 1.

In practice it is known that all processes are irreversible, and energy analysis is insufficient to deal with the problem accordingly. Consequently, it is apparent that exergy is needed as a potential tool to determine how much exergy destructions and losses take place in each component of the system and to require engineers to work on better system efficiency. Thus, the net flow rates of mechanical, thermal and work related exergies for each component in the Afyon GDHS are given in Table 2, where exergies are evaluated with respect to the reference state (case 1). Positive values of exergies indicate the exergy flow rate of “products” while negative values represent the exergy flow rate of “resources”. Here, the product of a component corresponds to the “added” exergy whereas the resource to the “consumed” exergy [31]. Negative values of the work exergies represent that work was done on the

Table 1
Thermal and mechanical exergy rates, entropy production rates and other thermodynamics properties at various system locations for the Afyon GDHS for case 1.

State no.	T (°C)	P (kPa)	$\dot{m}$ (kg/s)	$\dot{E}x^T$ (kW)	$\dot{E}x^P$ (kW)	$\dot{s}$ (kW)
0	2.3	101.32	–	–	–	–
1	99	183.34	100.0	5800.862	5.801	129.584
2	96	127.56	40.0	2189.918	2.190	50.470
3	98	212.21	40.0	2276.869	2.277	51.379
4	93	83.40	45.0	2320.939	2.321	55.233
5	95	94.85	175.0	9390.687	28.172	218.820
6	95.7	799.30	175.0	9523.831	142.857	220.212
7	93	70.56	175.0	9025.874	72.207	214.795
8	93	70.56	37.5	1934.116	15.473	46.028
9	51	48.87	37.5	604.886	6.654	26.873
10	93	70.56	38.8	2001.165	16.009	47.623
11	49	52.05	38.8	577.068	6.348	26.803
12	93	70.56	41.7	2150.737	17.206	51.183
13	52	46.45	41.7	698.933	7.688	30.420
14	93	70.56	27.8	1433.824	11.471	34.122
15	49	47.91	27.8	413.466	4.548	19.204
16	93	70.56	16.7	861.326	6.891	20.498
17	48	48.54	16.7	238.831	2.627	11.318
18	93	70.56	12.5	644.705	5.158	15.343
19	56	50.50	12.5	242.424	2.667	9.759
20	47.7	645.24	125.0	1765.193	26.478	84.225
21	47	331.23	125.0	1712.767	5.138	83.088
22	61	660.56	125.0	2867.130	43.007	105.475
23	47.7	635.45	138.9	1961.482	29.422	93.591
24	47	350.67	138.9	1903.227	5.710	92.327
25	60	650.90	138.9	3082.492	46.237	115.468
26	49.7	625.45	138.9	2124.100	31.861	97.216
27	49	370.20	138.9	2065.844	6.198	95.952
28	61	660.56	138.9	3186.940	47.804	117.176
29	49.7	580.67	97.2	1489.088	22.336	68.021
30	49	400.54	97.2	1445.645	4.337	67.146
31	60	610.89	97.2	2157.078	32.356	80.802
32	52.7	590.43	55.6	956.927	14.354	41.061
33	52	500.40	55.6	931.910	2.796	40.560
34	60	600.65	55.6	1233.884	18.508	46.220
35	52.7	555.34	41.7	717.696	10.765	30.795
36	52	510.90	41.7	698.933	2.097	30.420
37	60	560.00	41.7	925.413	13.881	34.665
38	12.4	220.45	10.0	7.604	18.250	1.863
39	–	–	–	–	–	–
40	–	–	–	–	–	–
41	12.4	410.45	1.9	1.445	4.334	0.354
42	12.4	410.45	2.8	2.129	6.387	0.522
43	12.4	410.45	2.8	2.129	6.387	0.522
44	12.4	410.45	2.5	1.901	5.703	0.466
45	50	70.56	175.0	2707.607	29.784	123.165
46	50	70.56	52.8	816.924	8.986	37.161
47	50	70.56	122.2	1890.683	20.798	86.004
48	50.7	800.45	122.2	1945.667	214.023	87.104

State no. refer to Fig. 1 for the Afyon GDHS. The values base on the measurements are taken in January 20, 2010.

components, simply work inputs to the pumps. Thermal water coming from the wells is treated as input, and useful exergy appears as output, based on the conversion from the resource to the product, respectively.

For case 1, according to Tables 1 and 2, the total exergy input of the system by considering geothermal wells and pumps to Afyon GDHS is 13,691.18 kW. 7.96% of exergy input is parasitic load to drive some components (especially pumps) in the system. Here, the thermal reinjection and the natural direct discharge account for respectively 15.77% and 6.03% of the total exergy input, while the mixing pool of the system cover its 23.24%. Finally, 25.34% of exergy entering the system (3469.88 kW) is converted to heating process (useful exergy). The remaining 17.25% of the exergy input is destroyed. This corresponds to 2361.67 kW, which is the total exergy destruction (or irreversibilities) in the Afyon GDHS. 69.10% of this is destroyed in the heat exchangers, 9.50% in the pumps and the remaining in the pipes as 21.40%, respectively. This shows that

Table 2
Exergy balances data of each component in the Afyon GDHS for case 1.

Component no.	$\dot{E}x^W$ (kW)	$\dot{E}x^T$ (kW)	$\dot{E}x^P$ (kW)	$\dot{s}$ (kW)
Heat exchanger				
I	0	−227.29	−25.35	197.29
II	0	−303.09	−26.48	273.09
III	0	−388.96	−25.46	358.96
IV	0	−352.37	−16.94	322.37
V	0	−345.54	−8.42	315.54
VI	0	−194.56	−5.61	164.56
Booster pump				
Pump 1	−315	133.14	114.69	67.17
Circulation pumps				
Pump 2	−90	52.43	21.34	16.23
Pump 3	−90	58.26	23.71	8.03
Pump 4	−90	58.26	25.66	6.08
Pump 5	−70	43.44	18.00	8.56
Pump 6	−50	25.02	11.56	13.42
Pump 7	−50	18.76	8.67	22.57
Pump of pressurized water tank				
Pump 8	−20	0.00	4.56	15.44
Reinjection pump				
Pump 9	−315	54.98	193.23	66.79
Pipes				
Pipes	0	−565.96	−71.40	505.56
Total	−1090	−1933.48	241.77	2361.67

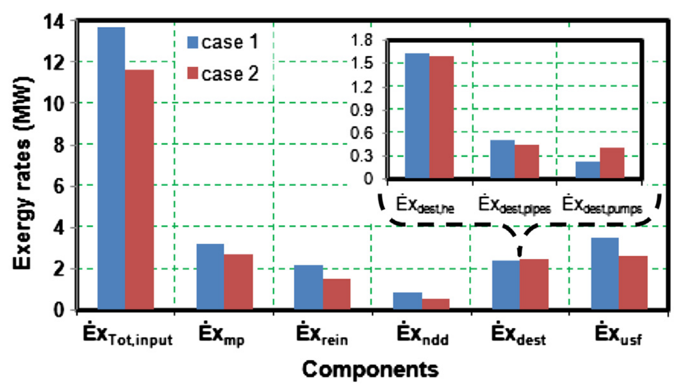

Fig. 2. Distribution of the exergy rates in the Afyon GDHS for each case.

the most considerable entropy production (exergy destruction) occurs in the heat exchangers due to the district heating supply temperature and a significant amount of water leaks in the piping system in both EPC and EDC. The district heating supply temperature should be selected as high as possible to increase the exergy efficiency of the heat exchangers and hence the whole system is consistent with the operating strategies.

The total exergy input values are obtained for 13.69 MW and 11.60 MW for cases 1 and 2, respectively, and presentation of how the varying ambient temperature affects the performance of the system, as shown in Fig. 2. According to this total exergy input, the exergy efficiency and total exergy destruction values are found to be 25.34% and 17.25% in case 1 and 22.78% and 21.09% in case 2, respectively. The reference (ambient) temperatures were 2.3 °C in January (case 1) and 10.2 °C in February (case 2). As expected, the lower the ambient temperature, the significantly larger the exergy destruction in the system's components. However, exergy rates of pipe losses of the system, heat exchangers, and useful exergy increase considerably. The reason for this rapid rise in exergy rates is due to a decrease in the ambient temperature as mentioned in Refs. [23,24,27,32].

It is obvious that the economic and performance of a GDHS can be improved enormously if the heat exchangers, pumps, pipes losses exergy flow rate are recovered accordingly. In Table 3, the

Table 3
Initial investments, annualized costs and corresponding monetary flow rates of each component in the Afyon GDHS for each case.

Component no.	Inital investment cost (US$)	Annualized cost (US$/year)	Monetary flow rate (US$/h)
Heat exchanger			
I	186,852	26,933.19	5.665
II	186,852	26,933.19	5.665
III	186,852	26,933.19	5.665
IV	127,320	18,352.14	3.860
V	127,320	18,352.14	3.860
VI	71,766	10,344.48	2.176
Booster pump			
Pump 1	15,318	2207.96	0.464
Circulation pumps			
Pump 2	3868	557.54	0.117
Pump 3	3868	557.54	0.117
Pump 4	3868	557.54	0.117
Pump 5	3352	483.16	0.102
Pump 6	2281	328.79	0.069
Pump 7	2281	328.79	0.069
Pump of pressurized water tank			
Pump 8	469	67.60	0.014
Reinjection pump			
Pump 9	15,318	2207.96	0.464
Pipes			
Pipes	6,920,930	997,595.42	209.812
Pipes	7,583,950	1,093,164.32	229.912
Total	15,442,465	2,225,904.94	468.147

Table 4
Cost flow rates of thermal, mechanical and entropy production of each component in the Afyon GDHS for case 1 (as of January 20, 2010).

Component no.	$\dot{C}_W$ (US$/h)	$\dot{C}_T$ (US$/h)	$\dot{C}_P$ (US$/h)	$\dot{C}_S$ (US$/h)	$\dot{Z}$ (US$/h)
Heat exchanger					
I	0	−11.296	−12.751	29.712	−5.665
II	0	−22.139	−13.323	41.127	−5.665
III	0	−35.583	−12.812	54.060	−5.665
IV	0	−36.164	−8.525	48.549	−3.860
V	0	−39.426	−4.236	47.522	−3.860
VI	0	−19.786	−2.821	24.783	−2.176
Booster pump					
Pump 1	−70.324	−0.283	60.955	10.116	−0.464
Circulation pumps					
Pump 2	−20.093	−0.113	17.878	2.445	−0.117
Pump 3	−20.093	−0.129	19.129	1.210	−0.117
Pump 4	−20.093	−0.128	19.422	0.916	−0.117
Pump 5	−15.628	−0.092	14.533	1.289	−0.102
Pump 6	−11.163	−0.053	9.263	2.022	−0.069
Pump 7	−11.163	−0.038	7.871	3.399	−0.069
Pump of pressurized water tank					
Pump 8	−4.465	0	2.154	2.325	−0.014
Reinjection pump					
Pump 9	−70.324	−0.118	60.847	10.059	−0.464
Pipes					
Pipes	0	169.602	−35.928	76.138	−209.812
Boundary	0	−4.254	−121.656	−355.669	−229.912
Total	−243.344	0.000	0.000	0.000	−468.147

initial investments, the annuity including the maintenance cost, and the corresponding monetary flow rates for each component of the Afyon GDHS are given for each case. These values are applied for each case. In the analysis, economic data are taken from managements of the Afyon GDHS and the producers of heat exchangers, pumps and pipes components for construction and other costs. And, the total construction cost includes the costs of well opening, plant preparation and building construction.

For case 1, the cost flow rates corresponding to exergy flow rate of each component and the construction cost are given in Table 4. The monetary flow rates of products are also given. The cost flow rates connected to the products and resources are used as the case of the exergy balances as listed in Table 2. The cost apparently results from the entropy production in each component as the consumed cost. Sum of the cost flow rates of each component in the Afyon GDHS equals zero, as shown in Table 3, and shows that cost balances for the each component are suitable. In the total system, the sum of the cost flow rates of electricity and capital expenditures of the GDHS equals zero, which is in fact a content of Eq. (13). Such result confirms that the overall cost balance as given in Eq. (13) is fully correct. The same manner is also confirmed for case 2, as can be shown in Table 5.

Table 5
Cost flow rates of thermal, mechanical and entropy production of each component in the Afyon GDHS for case 2 (as of February 23, 2010).

Component no.	$\dot{C}_W$ (US$/h)	$\dot{C}_T$ (US$/h)	$\dot{C}_P$ (US$/h)	$\dot{C}_S$ (US$/h)	$\dot{Z}$ (US$/h)
Heat exchanger					
I	0	−11.465	−13.963	31.093	−5.665
II	0	−20.698	−14.558	40.921	−5.665
III	0	−31.494	−14.113	51.272	−5.665
IV	0	−31.190	−9.369	44.419	−3.860
V	0	−32.706	−4.696	41.261	−3.860
VI	0	−16.636	−3.148	21.959	−2.176
Booster pump					
Pump 1	−70.324	−1.975	58.600	14.163	−0.464
Circulation pumps					
Pump 2	−20.093	−0.704	16.254	4.659	−0.117
Pump 3	−20.093	−0.781	17.269	3.722	−0.117
Pump 4	−20.093	−0.781	17.502	3.488	−0.117
Pump 5	−15.628	−0.596	13.270	3.055	−0.102
Pump 6	−11.163	−0.344	8.558	3.018	−0.069
Pump 7	−11.163	−0.251	7.402	4.081	−0.069
Pump of pressurized water tank					
Pump 8	−4.465	0	1.642	2.838	−0.014
Reinjection pump					
Pump 9	−70.324	−0.743	52.031	19.501	−0.464
Pipes					
Pipes	0	181.146	−37.632	66.298	−209.812
Boundary	0	−30.782	−95.049	−355.748	−229.912
Total	−243.344	0.000	0.000	0.000	−468.147

In the study, the system is operated with the exergy output of 3469.88 kW and 2643.57 kW in cases 1 and 2, respectively, and the unit electricity cost was 0.2233US$/kWh at that dates. The unit exergy costs are found as $c_P > c_T > c_S > c_Q$ for the studied actual data sets in each case. The cost structure discussed is a result of the expensive mechanical exergy which is derived from electricity.

As can be shown in Tables 4 and 5, about 52.49% and 64.91% of the input cost of the Afyon GDHS is lost in the heat exchangers, followed by the losses associated with 16.26% and 18.64% in pipes and 7.22% and 16.45% in pumps for cases 1 and 2, respectively. The cost flow rates lost in the components can be recovered completely in the form of thermal exergy. It should be noted that if the heat exchangers in the Afyon GDHS were designed bigger, they would have higher effectiveness and more energy would be recovered. This would increase the capital cost, decrease the exergy destruction in the heat exchange equipment, and decrease the production cost as a result. The selection of heat exchangers for the GDHS process is discussed in detail in Ref. [33].

Fig. 3 shows cost flow rates of all the components in the Afyon GDHS for each case. In Fig. 3(a), cost rate of exergy destructions as a function of second-law efficiency in each case are given for the heat exchangers. It is clear that as the ambient temperature increases the cost rate of exergy destruction ($\dot{C}_S$) of the heat exchangers decreases. This may be explained by expressing Eq. (11). Due to a increase in ambient temperature, thermal exergy costs convert to mechanical exergy cost. It should be noted that if the heat exchangers in the Afyon GDHS were designed bigger, they would have higher effectiveness and more energy would be

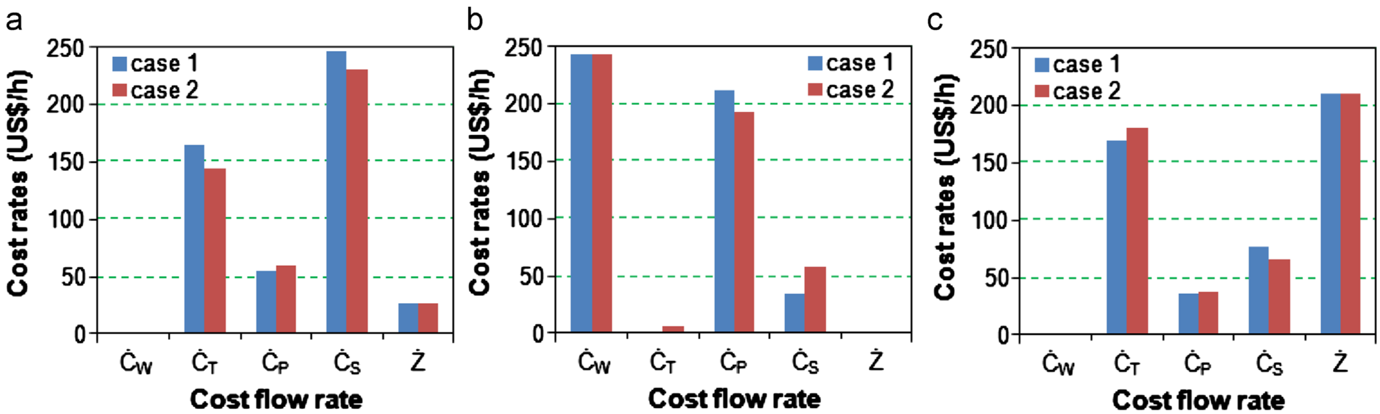

Fig. 3. Cost flow rates of (a) heat exchangers, (b) pumps, and (c) pipes for each case.

recovered. This would increase the capital cost, decrease the exergy destruction in the heat exchange equipment, and decrease the exergy cost as a result.

As all the pumps are operated in 100% load conditions for each case, Fig. 3(b) shows that the costs of electricity remain the same, and the cost of mechanical exergy decreases. However, the cost rate of exergy destruction of all the pumps increases. In many DHSs (especially the Afyon GDHS), most of the adjustments for system control (e.g. pump) are still performed manually. It can also lead to inaccurate control of ambient and water temperatures as well as flow rates, and then the buildings of the user are poor heated or over heated and cause energy waste. In these conditions, operating load of the system can be reduced or automatic control can be used, as the costs of pumping decrease. Besides, it is obvious that capital cost of all the pumps is very small according to the other exergy costs.

In pipes, since heat is in a tendency of transition from high temperature to low temperature, heat losses is formed in a heat transmission, hence, exergy losses depending on heat losses occur. Exergy destruction takes place because of the transport of hot water through pipes which occurred depending on the temperature between indoor and outdoor. According to various exergy rates of pipes, their cost flow rates in the Afyon GDHS are also shown in Fig. 3(c) for each case. It is clear that as capital cost rates of pipes for each case are are equal to each other due to same economic parameters. It is important to note that capital cost of pipes has higher than the others. When ambient temperature increases, the cost rate of exergy destruction caused by pipes decreases although cost rates of their mechanical and thermal exergies increase.

Finally, such a exergoeconomic optimization process (MOPSA), combining the exergy with economic analysis, will be useful in thermal engineering field. Especially, by calculating the exergy input, losses and output as well as economic evaluation with good accuracy, the degradation of the performance and economic points of view of the GDHS can be implemented.

5. Conclusions

This study deals with exergoeconomic evaluation of the Afyon geothermal district heating system (GDHS) and its components using a modified productive structure analysis (MOPSA). It is also shown that how exergy cost flow rates change with the ambient temperature. The actual system data sets (temperature, pressure, and flow rate) that were recorded in January 20 (case 1) and February 23 (case 2) 2010 at 100% load conditions are collected for this analysis. Mechanical and thermal exergy flow rates, entropy production rates and exergy cost flow rates for each component in the Afyon GDHS are calculated using these two actual data sets. Some comparisons are made on exergy cost flow rates for different ambient temperatures. Thus, the results allow us to better understand how the exergy cost is distributed among the components. The exergy efficiencies are found to be 25.34% and 22.78% in case 1 and case 2, respectively. The unit exergy costs are also found as $c_P > c_T > c_S > c_Q$ for the studied actual data sets in each case. About 52.49% and 64.91% of the input cost of the Afyon GDHS is lost from the heat exchangers, 16.26% and 18.64% from pipes, and 7.22% and 16.45% from pumps for cases 1 and 2, respectively. The cost accounting results show that the unit cost of heating from geothermal water in the Afyon GDHS is 711.491US$/h for each case at 100% load conditions. The results may also be used in an exergoeconomic optimization to minimize cost of GDHSs. In this regard, heat exchangers, the geothermal fluid leaving the system via natural direct discharge, and fluid in mixing pool should indicate the need for a heat recovery option as part of the system design and optimization. As a result, this study proves that ambient temperature has a big impact on the exergies and costs of GDHSs, and provides information on decisions about the design and operation of a GDHS to researchers and engineers in the energy field.

Acknowledgments

The author would like to thank for the support provided by the Afyon Geothermal Inc.

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